Selecting Appropriate Energy Storage Technology for use with a Residental Solar Photovoltaic Array

ENGN2225: System Engineering Design - Individual Portfolio

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Executive Summary

In this report the most suitable technology for use in conjunction with a solar photovoltaic array was explored, with the aim of minimising the clients’ energy use. The panels have been generating revenue by selling energy to the grid, though this will cease to be profitable at the end of this year when the government subsidy ends. In order to ensure the system maintains a high return, the clients’ wish to use the energy the produce directly. The design objective was therefore to minimise the quantity of electricity bought from the grid in order to maximise savings. A systems engineering approach was applied to thoroughly scope the problem, determine the key requirements, identify possible solutions and objectively evaluate their suitability. The design was required to minimise disruption to the clients’ energy use, be low cost, low maintenance and recyclable. Three battery technologies (lead-acid, lithium-ion and vanadium redox) were considered strong candidates for maximising self consumption of generated energy. Of these, it was decided that lead-acid batteries represented the lowest risk option due to low upfront cost and decades of use in solar applications, while the vanadium redox battery was the potentially the best option if the clients’ are willing to accept a higher risk.

Contents

Relevant situational and client information is provided and motivations for reducing grid dependence are discussed.

Choice of lead-acid or vanadium redox batteries as energy storage system is presented and discussed. Future actions for the client to take to realise the design are outlined.

The clients' existing solar PV system, its cost and revenue flow is discussed. Bounds for the remainder of the investigation established, excluding detailed analyses of battery chemistry from the scope.

The clients' needs, as established through interviews and correspondence are presented. They include minimising disruptions to supply, initial cost and maintenance needs and ensuring the system is recyclable.

The problem space is explored through brainstorming and possible solutions are categorised into usage changes, generation, storage and energy scavenging concepts. Storage is selected as the only branch worth further examination.

The necessary capabilites of the system are established, with the addition of a battery and switchboard to control power flow identified as the principle modifications.

An outline of the system architecture and the functions each subsystem will need to preform is established and discussed. The five subsystems were generation, supply, control, metering and usage. A mapping between functions, subsystems and stakeholders is provided to aid traceability in future.

The most important part of the system, the battery is tested and selected. Lead-acid, lithium ion and vanadium redox batteries are critically evaluated against each other using a range of criteria relating back to the customer requirements.

List of Figures

List of Tables

1 Introduction and Motivations

The clients' are a middle aged couple whose children have all left home. They own a large house in the Hunter Valley, with an existing solar photovoltaic array connected to the grid. They wish to investigate self-consumption of the energy they generate, to reduce grid dependence, minimise their environmental impact and eliminate electricity bills. The existing array generates more energy on average than the they use (see figure 5 in appendix B). The clients have been benefiting from the Solar Bonus Scheme (SBS) subsidised feed-in-tariff, but this is due to expire in December (DRE 2016).

The majority of Australia's energy needs are supplied by fossil fuels, with renewable sources accounting for only 2% of total supply (ABS 2016). The impacts of anthropogenic global warming are already being felt around the world and as citizens of a developed economy, Australian's have a responsibility to limit their contribution to greenhouse gas emissions. Australia has the highest average insolation of any continent (Nicholls, Sharma, and Saha 2015) making solar technologies a particularly effective renewable energy source. Solar photovoltaic cells have experienced large growth in recent years, including the widespread adoption of roof-top systems, fuelled by falling prices and government rebates and subsidies of energy feed-in-tariffs for residential consumers and small business. Some of the key strengths of residential solar power are its immunity to fuel cost induced price fluctuations, minimal operation cost and net negative greenhouse gas emissions over its lifetime. The principle drawbacks are the variable and intermittent power supply. These weaknesses can be effectively managed by coupling the solar panels to an energy storage system, enhancing the ability of owners to use the energy they generate (becoming 'prosumers').

In addition to reducing greenhouse gas emissions, investing in an independent renewable energy supply can have financial benefits. Generous government subsidies have made investment in solar panels attractive in recent years by funding feed-in-tariffs well above the retail price for electricity. Under these schemes, owners are paid for every kWh delivered to the grid and then buy back electricity from the grid at a lower rate. As the subsidies are wound back the focus of cost savings has shifted to direct consumption of the generated energy as market rate feed-in-tariffs are lower than the electricity price.

Section 2 discusses the key outcomes of the report and future direction for the project. The remainder of the report details the design process which lead to this conclusion. It is structured as follows: section 3 describes the existing system, explores and defines the problem space; section 4 establishes the clients' expectations of the design and refines these into technical performance measures; section 5 focusses on expansive thinking to ensure no novel solutions are overlooked; section 6 highlights the required functions the system must fulfil and establishes the basis for subsystems; section 7 details the interactions between subsystems and establishes a traceability map; finally section 8.1 critically evaluates the most suitable battery system against a wide range of criteria.

2 Recommended Design

The proposed solution is to overhaul the existing solar array so the clients' can self-consume the energy they generate, time-shift energy for use at night by installing a battery and still sell the excess to the grid. The preferred batteries for this purpose are lead-acid (Pb-A) and vanadium redox batteries (VRB). Lead-acid batteries have the advantage of being cheap and reliable, but suffer from low energy density and relatively short lifetime. Vanadium redox batteries have comparable energy density, much longer lifetime, low sensitivity to variable charge and discharge cycles but cost more and have not been used in residential scale applications for long. If the clients' are willing to accept a slightly higher level of risk and longer payback time then it is recommended to choose the VRB. Otherwise Pb-A batteries are recommended to obtain a short payback time with low level of risk.

As the solar feed-in-tariff subsidy is due to expire at the end of this year, future work on this project should focus on determining an appropriate size for the battery, estimating acquisition and installation costs, determining the expected cost payback time and further evaluating the battery characteristics by investigating commercially available models. In the next six months it is advised that the clients engage with a range of suppliers and installers to assemble a list of alternatives, compare prices and scope options for system sizing. Ideally the final investment decision should be made such that the system can be installed in January 2017, taking the lead time for products into account.

3 Problem Scoping

3.1 Existing system description

The currently installed system includes a 10 kW solar photovoltaic array, an inverter, smart meter and a connection to the grid. The system was installed in early 2011 at a cost of around $55000 which included the panels, footings, inverters, meters and installation (C & R Logan, pers. comm.)). The existing infrastructure is intended solely for feeding power to the grid and does not incorporate a switchboard to allow self-consumption. The generated energy exceeds the clients' consumption on average in summer months, but does not always match the demand in winter (C & R Logan, pers. comm.)).

Revenue generated through the subsidised feed-in tariff has partially offset the installation cost of the system. At the time of construction the SBS was fixed at $0.66/kWh, this was reduced to $0.6/kWh in late 2012 and has remained at that level ever since. The subsidy is due to expire in December 2016 (DRE 2016) after which the feed-in-tariff will drop to the utility suppliers rate of $0.051/kWh (AGL 2016), which is below the retail price of electricity. The income from subsidised tariff has exceeded the clients' spending on electricity, with total revenue of $35200 since coming on-line. The system has not yet paid back the cost of the initial investment however.

3.2 Stakeholder analysis

A number of stakeholders interact within the problem scope and have varying degrees of control, most commonly over the various costs and returns. The user has the greatest level of control over the future direction of the system as it is a private development but there are strong influences from the government and utility suppliers who regulate the cost of electricity and the solar feed-in-tariffs. The cost payback time of residential solar arrays is particularly sensitive to the electricity price, more so than the tariff (Nicholls, Sharma, and Saha 2015) in a situation where battery storage is in use. The utility supplier has a strong interest in retaining the client as a customer, while the supplier of any new systems has a strong interest in selling its products, but limited capacity to guide the owners choice. The installer has greater influence as the owner will acquire components through them. The environment stands to gain the most due to lower green house gas emissions, but cannot directly influence anyone. The map in figure 1 shows that the most important stakeholders for the clients' to engage with are the installer and utility provider.

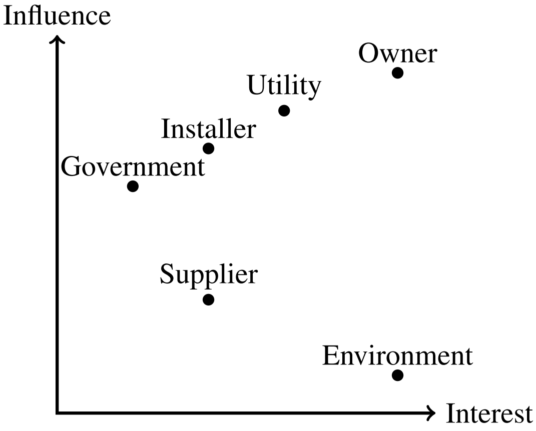

Figure 1: Stakeholder interest-influence map

3.3 System boundary

The diverse variables which impact on a solar power system were assessed and categorised to focus the problem scope on critical factors. The size of any generation or storage system installed can be chosen by the owner and as such these were considered internal variables, as was the capability to switch between supplying the house and exporting energy to the grid. In addition the average energy use of the owners was treated as internal to the system as it represents habitual usage patterns, which can be altered. The peak energy use was considered to be external as it could depend on weather conditions, seasons, time of day and other variable factors. The impact of seasons on solar PV was deemed important but cannot be controlled. The degradation of both the existing panels and any new system was included in the external variables as it could have a significant long-term impact on the system. Many of the details of installation, regulations which may effect this and effects on property values were chosen to be outside the scope as this project focussed on only the critical points.

Table 1: System boundary chart

Internal	External	Excluded
Generation capacity	Seasons	Weather
Energy storage	Installation cost	Impact on neighbours
Switching capability	Maintenance cost	Council development requirements
Cost of storage	Degradation of storage and panels	Impact on property value
Average energy use		End-of-life dismantling
		Change of ownership
		Aesthetic impact
		Embodied energy
		Electrical connection details
		Location of system
		Efficiency of solar panels
		Battery chemistry
		Peak energy use
		Model specifications

Table 2: Mapping of the customer requirements to technical performance measures. For the Change ↑ is to maximise, ↓ to minimise and • to optimise.

Customer requirements	Rank	Design Requirements	Metric	Change	Benchmark
Minimal Disruption	1	Voltage	V	•	240
		Frequency	Hz	•	50
		Storage	kWh	↑	10
		Availability	%	↑	100
		Degradation	% /yr	↓	1[1]
Easy to Maintain	3	Maintenance Cost	$/yr	↓	400
		Maintenance Time	hr/yr	↓	8
		Lifetime	yr	↑	20
Recyclable	4	Recyclable mass	%	↑	95
		Recycled mass	%	↑	95
Cheap	2	Install cost	$	↓	15000
		Electricity cost savings	$/yr	↑	3000
		Cost Pay Back Time	yr	↓	5

4 Requirements Analysis

An interview with the clients was conducted to elucidate their needs and expectations of the system. The customer requirements were ranked and then systematically broken down into a set of technical performance measures.

4.1 Requirements Mapping

Through discussions with the client it was established that the most important requirements for the system were:

1. No disruption during or after transition regarding power availability; retention of current appliances and lifestyle change. The quality of service should not degrade over time.
2. System should require minimal maintenance, be easy to fix if needed and be upgradeable in future. It should be reliable, fault tolerant and have a long useful life.
3. Recycled content should be used as much as possible and at end-of-life the system should be recyclable.
4. The cost payback time on the investment should be a few years.

The customer requirements were decomposed into a range of measurable design criteria which could be used to evaluate alternative architectures. These are presented together with the associated customer requirements, metrics, direction of desired change and benchmark standards in table 2.

The key customer requirements were expected to have complex interactions and as such a priority ranking was needed. The most important was evidently minimising disruption to the clients usage patterns, particularly in light of the intermittent nature of solar power. Keeping the initial cost down was considered more important than minimising maintenance as the clients are not likely to make the additional investment if the system cannot pay itself back within a few years (C & R Logan, pers. comm.)). The ranking shown in table 2 was communicated to the clients and accepted as appropriate without modification.

The technical performances measures were assigned benchmarks to assist the evaluation of potential solutions. Those for availability, lifetime, recycled content, install cost and cost payback time were determined through discussions with the client(C & R Logan, pers. comm.)). The voltage and frequency were chosen to match the standard for Australian power supply. The size of the battery system was chosen to give a high level of independence from the grid and enable the clients to take most advantage of the energy generated by the panels. Larger battery sizes are critical in increasing the economic viability of solar arrays as a primary source of power according to modelling conducted by Khalilpour and Vassallo 2015. In particular, they found that for a house consuming around 8500 kWh per year, a 10 kW PV system coupled with a 10 kWh battery could supply 60% of the energy need. In addition, increasing the size of the solar array beyond 10 kW had a much less pronounced impact on grid independence. The clients annual energy use is somewhat lower than that used in the study and as such a 10 kWh storage system seems appropriate.

5 Idea Generation

A systematic approach was used to fully explore the problem space. The key ideas which emerged during this process included adjustments to usage patterns to reduce energy consumption, increased generation capacity, augmenting the existing system through use of energy storage and installing an energy-scavenging network. It was concluded that the most suitable option would be the addition of energy storage, with battery technologies offering the most promising way forward.

5.1 Structured Brainstorming

Ideas were brainstormed in four distinct categories: full independence from the grid, partial independence, high cost options and relatively cheap alternatives. The results are shown in table 6 in appendix B. There was a significant amount of overlap between high cost and full independence, which suggests these categories are not really distinct. This pattern was repeated in the partial and low cost categories.

5.2 Concept Generation

The results from the structured brainstorm, were condensed into a more controllable range of options through use of a classification tree. Four distinct concepts emerged through this process as shown in figure 2. The storage option immediately seemed more attractive due to the plethora of options available, while usage reduction seemed the most easily achievable, energy scavenging the least useful and extra generation unnecessary.

The concept of reducing usage has already been adopted to a certain extent as the clients use energy saving bulbs in most lighted areas and have installed skylights in some rooms. For a two person household, the clients' energy usage is already below average for their area according to their electricity bills. Currently the clients' power usage pattern involves using energy hungry appliances such as washing machines, water heaters, dish washers etc. during the off-peak period from 10pm-7am when electricity is cheapest (C & R Logan, pers. comm.)). If this concept was coupled with an altered connection arrangement allowing supply consumption, then the clients could alter their usage pattern to take advantage of the electricity they generate during the day, reducing their overall consumption.

The concept of storage was considered particularly promising since batteries could be used to augment the existing solar array. This is an essential component of self-consumption systems and is widely employed in this capacity. Hydrogen storage would be used in conjunction with a fuel cell by using power from the solar array to synthesise hydrogen through the fuel cell and then reversing the process to supply power when needed. The major drawback of hydrogen storage is the necessity of installing an expensive fuel cell, without offering advantages over an electrochemical battery. Common battery technologies used for large scale stationary energy storage include lead-acid, lithium ion, redox-flow batteries, sodium sulphur (NaS), nickel metal hydride (Ni-MH), nickel-cadmium (Ni-Cd) and sodium nickel chloride (ZEBRA) (Chen et al. 2009). Of these technologies, the NaS and ZEBRA batteries were discounted due to their high (300 °C) operating temperatures (Chen et al. 2009) (Leadbetter and Swan 2012). The NiCd battery was deemed inappropriate due to the environmental impacts of toxic cadmium and the necessity of carefully managing the battery to prevent loss of capacity due to the memory effect (Chen et al. 2009). According to Hoppmann et al. 2014 and Balcombe, Rigby, and Azapagic 2015, lead-acid batteries are the dominant technology used in small scale residential applications due to their reliability, small self-discharge and low upfront cost. Lithium ion technologies currently account for the largest share of storage applications worldwide according to Malhotra et al. 2016. This review incorporates large scale storage in addition to residential systems and hence may not be applicable.

The generation concept explores options for supplementing the existing capacity of the solar array. The diesel generator was deemed to be inappropriate due to the necessity of importing fuel, lower efficiency compared to fossil fuel power stations and lack of monetary return. Fuel cells were considered to be favourable due to their reliability and regularity of supply. Residential models are not available in Australia at present however and would have to be imported (Nicholls, Sharma, and Saha 2015)(Horin and Dicks 2009), increasing the acquisition cost. A fuel cell shares the need for an external supply of fuel with the diesel generator. Hybrid solar-wind systems have the potential to provide a more stable power supply(Zhou et al. 2010). A wind turbine was considered inappropriate however, due to the location of the property in the centre of town and limited space for the construction of a tower. After consultation with the client this route of inquiry was abandoned (C & R Logan, pers. comm.)). In addition, the existing power supply already exceeds usage on average and investing in additional generation capacity would not solve the problem of intermittent supply from the panels.

The energy scavenging concept was deemed to be too expensive and low power to be practical at this time. Energy scavenging devices require constant sources of low level input across a very large collection area to generate useful amounts of energy. Micro-solar is redundant compared to the existing array and piezoelectric devices would not be triggered regularly. Peltier devices potentially could be useful in summer if placed in the roof cavity. These type of devices are generally only suitable for very low power applications and hence are not useful in the context of powering a household.

The key conclusion drawn from the idea generation was that the most practical means of going off-grid would be to augment the existing solar PV array rather than installing an additional source of power generation. From this point onwards, research was focussed on designing and evaluating an effective battery storage system.

6 Logic and Function

Leading on from the conclusions drawn in section 5.2, the proposed solution will involve incorporating battery storage into the existing system and conceiving a method of supplying energy directly to the house from the solar array. It was chosen to maintain the grid connection in order to ensure constant availability and to maximise the financial return by selling excess energy to utility suppliers. This configuration was more practical than removing the house from the grid entirely (Khalilpour and Vassallo 2015).

6.1 Functional Flow

A functional flow of the proposed system, incorporating battery storage and switching capability is shown in figure 3. It demonstrates the method of supplying power to the house dependent on the availability of solar power and stored energy. It includes the capability to export energy to the grid when there is excess supply and to import when there is a deficit. This ability to control the flow of power can be implemented using commercially available meters with an inbuilt switchboard, monitoring and control system.

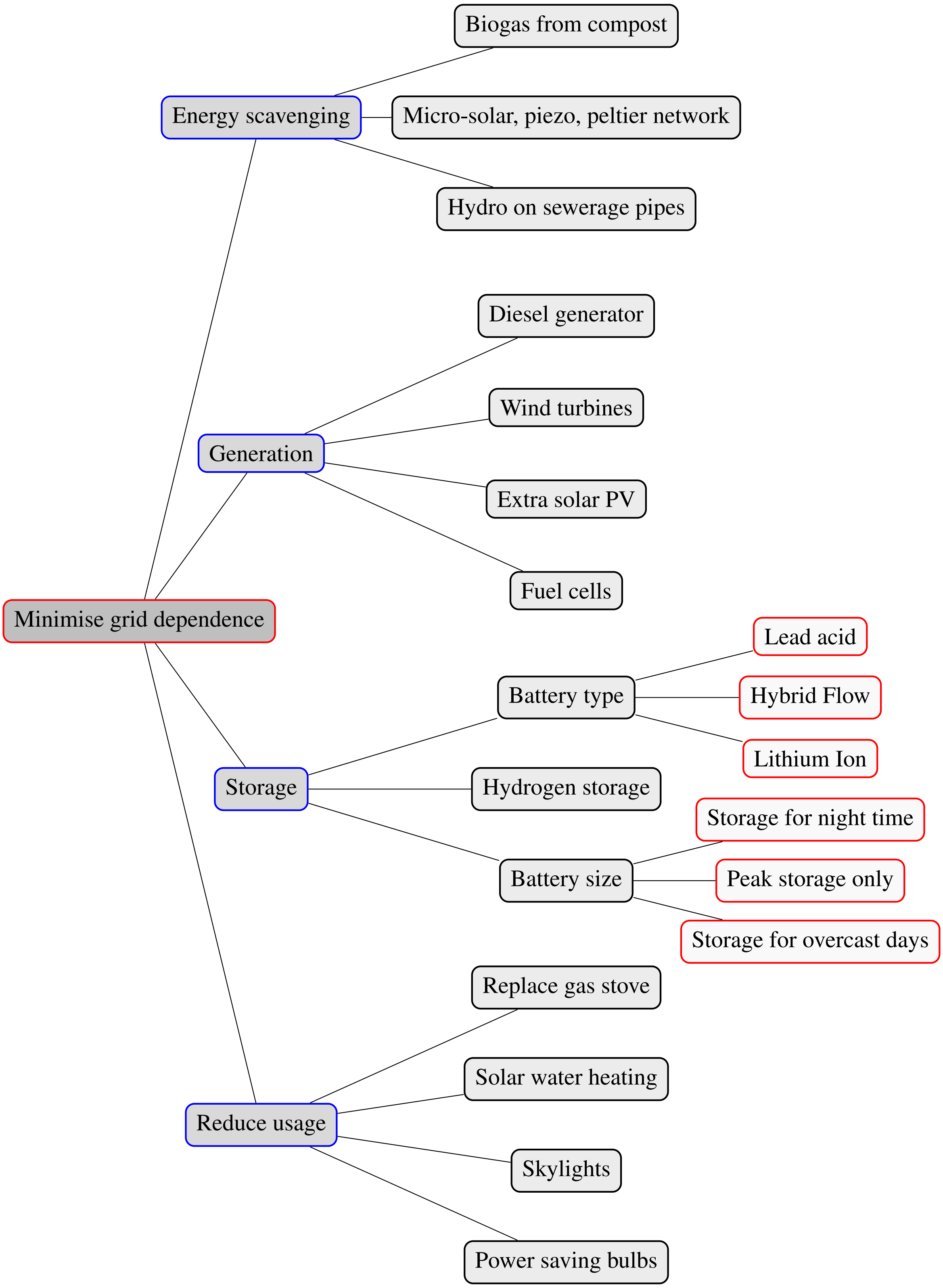

Figure 2: Concept generation tree built on the brainstorming results

To maximise the financial return on the clients investment the available solar power must be utilised effectively. At many times, particularly in summer the existing solar array generates more power than the household consumes. In these situations it is desirable to harness this excess energy by storing it for periods when the panels cannot meet demand such as during the night and on overcast days. Any battery system will have limited storage capacity and when this capacity is reached the system should be able to divert supply to the grid to take advantage of the feed-in-tariff.

The flow diagram assisted in highlighting the variety of functions which the system needs to fulfil in order to operate effectively. These are described in table 7 and are assigned to specific subsystems and stakeholders in section 7.2. Some functions, such as Regulate and Record are already covered by the existing inverter and smart meter respectively as detailed in section 3.1.

7 System Architecture

The subsystems isolated using the functional flow were developed into the more compact subsystem interface as shown in figure 4.

7.1 Subsystem Interface

The subsystem interface for the independent power supply is shown in figure 4. The subsystems and components of each naturally fall into the arrangement shown, but the interactions were not so obvious. The usage subsystem represents all devices and appliances on the property with require electrical supply. The user interacts with this subsystem from outside the system, although some of the components are automatic, such as the water heater or permanently on (security system) and do not require user input on a regular basis. The control subsystem was intended to handle all monitoring and power flow management for the system. The metering capability was included as part of this subsystem in its second iteration after further analysis and research revealed that a single device could handle both sets of functionality. The generation subsystem incorporates the panels and associated inverter, although both these components have interactions with external subsystems, indicating that in a further iteration it may be appropriate to rearrange these. This was of particular concern since power supply from the battery needs to go back through the inverter before being fed to the usage subsystem. Framework and cabling for the panels was not explicitly included as it is already installed and the specifics were considered outside this reports scope.

7.2 Subsystem Mapping

The stakeholders, design requirements, functions and subsystems as developed in sections 3.2, 4.1, 6.1 and 7.1 respectively were condensed into a single mapping to allow for traceability. This is shown in table 3 which clearly highlighted the importance of the installer and supplier across a wide range of functions. It also revealed that the availability and capacity requirements are closed linked.

8 Validation and Evaluation

8.1 Testing

To accurately determine which options to select for the final system, tests were devised for each of the subsystems to evaluate suitable options. The most complex testing centres around the choice of battery in the supply

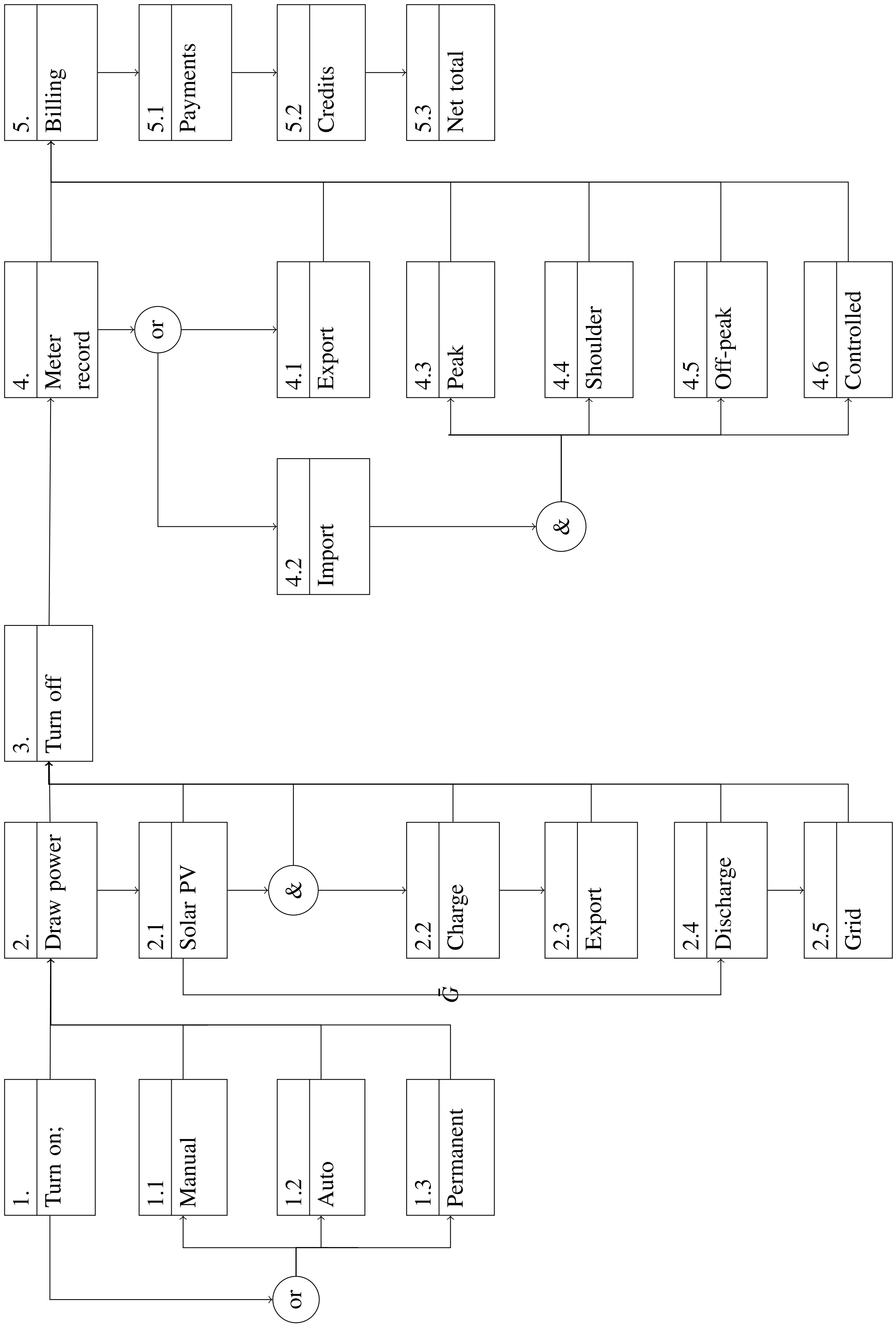

Figure 3: Functional flow describing the power supply with battery storage and a switching system to allow the panels to power the household directly.

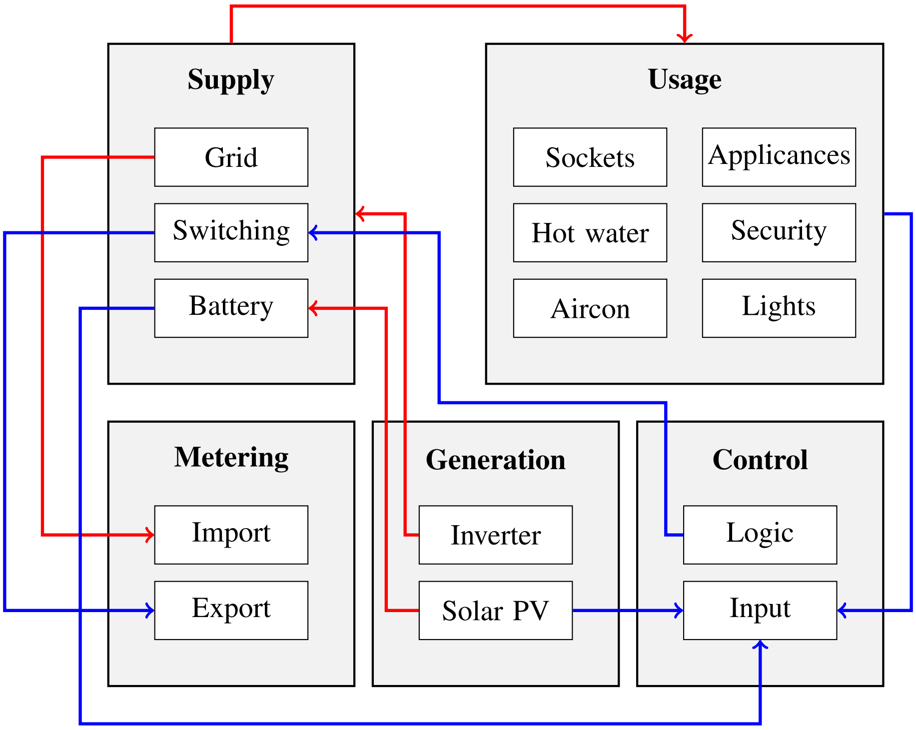

Figure 4: Subsystem interface for the power supply system with storage and backup grid connection. Red arrows denote a flow of energy (used synonymously with power), while blue arrows denote an information flow.

subsystem. Advanced metering devices, capable of controlling the flow of power between panels, battery, household and grid are commercially available

Detailed testing of the generation system was not undertaken due to limitations in the data, which includes only monthly generation energy. Important observations from the client are mentioned in brief. As has been stated already, the panels generate more energy than the clients consume on an average basis. Supply does not always meet demand in winter however, particularly during times of peak load. The panels have required not significant maintenance, being cleaned by the clients once annually and have demonstrated no faults at any time. The meters and inverters currently in place have also required no maintenance and demonstrated no problems.

The control and metering subsystems must receive accurate real time data and be able to adjust the flow of

Table 3: Mapping of functions to the associated design requirements and the subsystem which will be responsible.

Functions	DRs	Subsystem	Stakeholders
Supply power from panels	Availability	Gen., Sup.	User, Inst.
Regulate current from panels	Voltage, Frequency	Sup., Con., Gen.	Sup., Inst.
Charge battery from panels	Availability, capacity	Gen., Con.	Inst., Sup.
Discharge battery	Availability, capacity	Sup., Con.	User, Sup., Inst.
Export to grid	CPBT	Sup., Con., Met.	Gov., Ute.
Import from grid	Availability	Sup., Con., Met.	Ute.
Record import and exports	Electricity savings, CPBT	Met.	User, Inst., Ute.
Switch between DC and AC voltages	Availability, capacity	Gen., Sup., Con.	Inst., Sup.
Monitor efficiency	Degrad., Maint., life	Con., Met.	User, Inst., Sup.

Table 4: Metrics used to compare lead-acid, redox-flow and lithium-ion technologies.

Design Metric	Pb-A	VRB	Li-ion
Cycle efficiency	72-87	73-83	88-97
Capital cost	200-500	150-1000	600-2000
Energy density	30-50	10-30	75-200
Lifetime (cycles)	350-2000	10000+	2000-10000
Self discharge rate	0.1-0.5	0	0.1-0.5
Maturity	Mature	Developed	Developed

power to suit the immediate supply and loading conditions. The metering system should be able to accurately measure the quantities of energy exported and imported from the grid and reliably deliver these results to the user and utility supplier. Testing of this logic was considered to be outside the scope of this report but should be explored in future work.

The three chosen battery technologies, lead acid (Pb-A), lithium ion (Li-ion) and redox flow have all been extensively tested in the past. There remain significant uncertainties around the full life cycle cost of each of these technologies (Battke et al. 2013), with no distinct leading type. Each of these technologies have been used in large scale energy storage applications, including for renewable energy systems.

The key metrics for evaluating battery performance are listed in table 4. The data were synthesised principally from Chen et al. 2009 and Leadbetter and Swan 2012, both reviews of current battery technology. A number of values were also sourced from or compared to Wang, He, and Zhou 2012, Battke et al. 2013 and Toledo, Filho, and Diniz 2010. The values presented for the flow-battery relate specifically to vanadium redox batteries (VRB) as there was more data for these available in the sources.

For the household in question, the most important considerations were deemed to be the capital cost, lifetime, discharge time, depth of discharge and self discharge rate. The rated power and power density were considered less important due to the relatively low loadings required for the household.

The data in table 4 addresses the first two customer requirements (see table 2) of minimising disruption and cost. In addition to this flow-batteries have the advantage of increased flexibility as the power rating and storage capacity can be scaled independently.

Currently over 90% of lead-acid batteries are recycled in Australia (Lewis 2010) thanks to well established techniques and infrastructure. Recycling processes also exist for lithium ion and redox-flow technology but at present these are either not commercially favourable or do not have sufficient infrastructure to ensure a high rate of recycling.

8.2 Evaluation

The most important choice in the design of this system is which battery technology should be used to provide storage capacity. As such the evaluation focussed on determining which of lead-acid, lithium-ion or redox-flow batteries would be most suitable for the client. As costs for storage and power ratings were compared on a per kWh (kW for power) basis, the precise sizing of the system was left undetermined at present. In discussions with the client (C & R Logan, pers. comm.)), it was determined that a system capable of partially powering the house was the favoured option.

The key advantages of lead-acid technology are the low initial cost, established recycling infrastructure (Lewis 2010) and the predictability that goes with maturity. Modelling by Battke et al. 2013 found that lead-acid batteries were the most cost effective technology for increasing residential self consumption when compared

Table 5: Evaluation matrix used to compare battery options.

Requirement	Rank	Weight	Lead Acid		Lithium Ion		Redox flow	
			Score	Weighted	Score	Weighted	Score	Weighted
Disruption	1	4	3	12	4	16	5	20
Cheap	2	3	5	15	2	6	3	9
Easy maintenance	3	2	4	8	4	8	4	8
Recycling	4	1	5	5	2	2	4	4
Totals				40		32		41

with lithium-ion, vanadium redox and sodium sulphur batteries. The required level of maintenance is dependent on battery construction, cheaper wet cells need regular topping up with distilled water, while more expensive gel batteries are maintenance free (Speidel and Bräunl 2016). Disadvantages include the relatively short life cycle and mediocre energy density.

Redox-flow batteries have a distinct advantage in longevity and flexibility. The ability to be 100% discharged without impacting battery performance, negligible standby loss and the decoupled power and energy ratings allow for the greatest range of customisation and flexible use. Flow batteries require negligible maintenance and are relatively straight forward to recycle. In addition, the process for recycling flow-batteries is relatively straightforward (Battke et al. 2013) and the stability of electrolytes could facilitate their reuse. Some residential scale models are available in Australia (e.g. Redflow). The negatives of flow batteries include the very low energy density, relatively high cost and limited data from prior use on a residential scale.

The energy density and cycle efficiency of lithium-ion batteries is higher than any other widely available battery technology. Combined with long lifetime this makes them the most compact choice. Like lead-acid and flow batteries they require no maintenance (Nicholls, Sharma, and Saha 2015). Residential models are available in Australia (e.g. Samsung and Tesla). Recycling processes exist for common lithium-ion technologies, however it is unclear whether these processes are economical (Chagnes and Pospiech 2013),(BCI 2016) due to the complexities associated with extracting valuable materials. Key disadvantages are the high cost, complex and uneconomical recycling processes and limited prior experience of residential applications.

A weighted evaluation matrix was chosen to objectively compare the battery technologies as shown in table 5. The scores assigned the ’Disruption’ and ’Cheap’ requirements were drawn directly from the data presented in table 4, supported by other evidence discussed in section 8.1. The VRB achieved the highest in the evaluation, but is comparable to the lead-acid battery. Due to uncertainties in the data, particularly with regards to maintenance and recycling, these can be treated as effectively the same score. The gap between these two technologies and Li-ion was considered to be more significant.

Based on these results it was concluded that the lead-acid and vanadium redox technologies were equally suitable for the clients’ purpose but for different reasons. Lead-acid batteries have the advantage of lower cost and a longer history of use in similar applications. The vanadium redox battery is superior in terms of lifetime, flexibility and has negligible degradation. Both require minimal maintenance and are easily recycled, although recycling infrastructure is well established for lead-acid batteries only. Therefore the final choice of technology will be put to the client as described in section 2.

Acknowledgements

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References

ABS (2016). *Energy Account, Australia 2013-14*. cat. no. 4604.0. Australian Bureau of Statistics. URL: `http://www.abs.gov.au/AUSSTATS/abs@.nsf/Latestproducts/4604.0Main%20Features12013-14?opendocument\&tabname=Summary\&prodno=4604.0\&issue=2013-14\&num=\&view=` (visited on 04/26/2016).

AGL (2016). *Solar power feed-in tariffs for New South Wales*. AGL Energy. URL: `https://aglsolar.com.au/solar-power-feed-in-tariffs-in-new-south-wales/`.

BCI (2016). *Lead Acid Batteries*. Battery Council International. URL: `http://batterycouncil.org/?page=Lead_Acid_Batteries`.

Balcombe, P., D. Rigby, and A. Azapagic (2015). "Environmental impacts of microgeneration: Integrating solar PV, Stirling engine CHP and battery storage". English. In: *Applied Energy* 139, pp. 245–259.

Battke, B. et al. (2013). "A review and probabilistic model of lifecycle costs of stationary batteries in multiple applications". English. In: *Renewable and Sustainable Energy Reviews* 25, pp. 240–250.

Chagnes, A. and B. Pospiech (2013). "A brief review on hydrometallurgical technologies for recycling spent lithium-ion batteries". English. In: *Journal of Chemical Technology and Biotechnology* 88.7, pp. 1191–1199.

Chen, H. et al. (2009). "Progress in electrical energy storage system: A critical review". In: *Progress in Natural Science* 1.3, pp. 291 –312. ISSN: 1002-0071.

DRE (2016). *Solar Bonus Scheme ends 31 December 2016*. NSW Government: Dept. Resources and Energy. URL: `http://www.resourcesandenergy.nsw.gov.au/energy-consumers/solar/solar-bonus-scheme/solar-bonus-scheme` (visited on 05/01/2016).

Fthenakis, V. et al. (2011). *Methodology Guidelines on Life-Cycle Assessment of Photovoltaic Electricity*. IEA PVPS Task 12. International Energy Agency Photovoltaic Power Systems Programme.

Hoppmann, J. et al. (2014). "The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model". In: *Renewable and Sustainable Energy Reviews* 39, pp. 1101 –1118. ISSN: 1364-0321.

Horin, A. and A. Dicks (2009). "Fuel Cells in Australia". In: *Ecogeneration* (53), pp. 64–65.

Khalilpour, R. and A. Vassallo (2015). "Leaving the grid: An ambition or a real choice?" In: *Energy Policy* 82, pp. 207 –221. ISSN: 0301-4215.

Leadbetter, J. and L.G. Swan (2012). "Selection of battery technology to support grid-integrated renewable electricity". English. In: *Journal of Power Sources* 216, pp. 376–386.

Lewis, H. (2010). "Increased battery recycling in Australia will help to conserve non-renewable resources and reduce pollution from landfills". In: *Battery Waste and Recycling* (92), pp. 24–27.

Malhotra, A. et al. (2016). "Use cases for stationary battery technologies: A review of the literature and existing projects". English. In: *Renewable and Sustainable Energy Reviews* 56, pp. 705–721.

Nicholls, A., R. Sharma, and T.K. Saha (2015). "Financial and environmental analysis of rooftop photovoltaic installations with battery storage in Australia". English. In: *Applied Energy* 159, pp. 252–264.

Speidel, S. and T. Bräunl (2016). "Leaving the grid—The effect of combining home energy storage with renewable energy generation". English. In: *Renewable and Sustainable Energy Reviews* 60, pp. 1213–1224.

Toledo, O.M., D.O. Filho, and A.S.A.C. Diniz (2010). "Distributed photovoltaic generation and energy storage systems: A review". In: *Renewable and Sustainable Energy Reviews* 14.1, pp. 506 –511. ISSN: 1364-0321.

Wang, Y., P. He, and H. Zhou (2012). “Li-Redox Flow Batteries Based on Hybrid Electrolytes: At the Cross Road between Li-ion and Redox Flow Batteries”. English. In: *Advanced Energy Materials* 2.7, pp. 770–779.

Zhou, W. et al. (2010). “Current status of research on optimum sizing of stand-alone hybrid solar–wind power generation systems”. English. In: *Applied Energy* 87.2, pp. 380–389.

A Reflection

Creating this portfolio was challenging, at times stressful, but most importantly it was interesting. Very few pieces of assessment stimulate my interest in a subject these days but the relatively open ended scope of this project allowed me to focus on something that I actually care about.

This final version of the document is far from my initial expectations of the project. The starting scope was to make my family home completely independent of both the electricity grid and mains water supply. It very quickly became apparent through research and discussion with the clients (my parents) that this was infeasible if I wished to meet their main criteria of not dramatically disrupting the quality of service they receive. Other evolutions like this occurred throughout the design process, at many different stages and so the results of the project fell short of my expectations and pointed in quite a different direction. I do not consider this work to be complete and intend to pursue this line of inquiry further, though in a less formal setting. I have become quite invested in seeing my work come to fruition in the near future, as my research has convinced me of the potential economic benefits of installing a battery.

I found that the TCs I had completed were not possible to include in the final report as the scope had evolved too much (in particular I changed topic entirely after the first 2 TCs). The did however enrich my understanding of the tools and topic. All the TC text and diagrams were overhauled and improved upon while writing the portfolio.

I did not find the peer review feedback to be particularly helpful overall. Many of the comments made by the reviewers were either obvious to me/generic (e.g. talk more about why the tools you have used were useful) and on some occasions I disagreed with the feedback (e.g. your argument flows very well; I thought it was disjointed at that stage). Some of the useful comments helped me to restructure the discussion based around the concept tree to lead by emphasising the benefits of battery systems more before discounting other options.

In order to finish this portfolio the scope had to be greatly reduced. Given more time I would have proceeded to conduct a detailed costing of potential systems, explored commercial options for batteries and determined whether the existing inverter and meters would need replacing in order to be compatible. If I had to do this project again, I would attack the problem with the assumption that a battery would be installed and focussed on developing a more detailed design.

B Additional tables and figures

Results of the structured brainstorm are laid out in table 6. Details of the functions referred to in the subsystem mapping (table 3) are given in table 7. The historical time series data for the average daily generation of the solar PV array is shown in figure 5.

Table 6: Structured brainstorm results

Full Independence	High Cost
• Solar PV on front roof • Solar hot water • Battery with excess capacity for overcast days • Lithium ion battery • Flow battery • Lead-acid battery (deep cycle, wet cell) • Fuel cell and hydrogen storage • Replace gas stove • Wind turbines • Cooperative community project with neighbours • Diesel generator • Hybrid system of multiple renewable sources	• Fuel cell with hydrogen storage • Replace existing panels with higher efficiency ones • Replace heating with underfloor system • Large capacity storage • Replace existing fixed panel mounts with an active tracking design • Solar thermal array • Energy scavenging – biogas, micro-solar, piezoelectric, Peltier
Partial Independence	Low Cost
• Divert solar power to house when available • Storage for peak consumption and night time • Wind turbine with battery (not connected to panels)	• Battery storage for night only • Energy saving lights and low power appliances • Skylights • Solar water heating • Double glazed windows and better insulation • Change usage patterns to minimise energy use

Table 7: Function breakdown based on figure 3.

Function	Description
Panels	Supply power directly to the house as it is being generated by the panels
Charge	Charge the battery to full capacity using excess power not needed to supply the house
Export	Export excess energy to the grid when the battery is fully charged
Discharge	Discharge the battery to supply the house when the panels do not meet demand
Import	Import energy from the grid when the battery is fully discharged and panels do not meet demand
Regulate	Convert DC output from panels and battery to standard 240 V 50 Hz AC supply
Control	Control switching of the system between the various modes of operation as power supply and demand change
Record	Monitor and record energy imports and exports
Monitor	Long-term monitoring of panel output and battery charge cycle to track system degradation

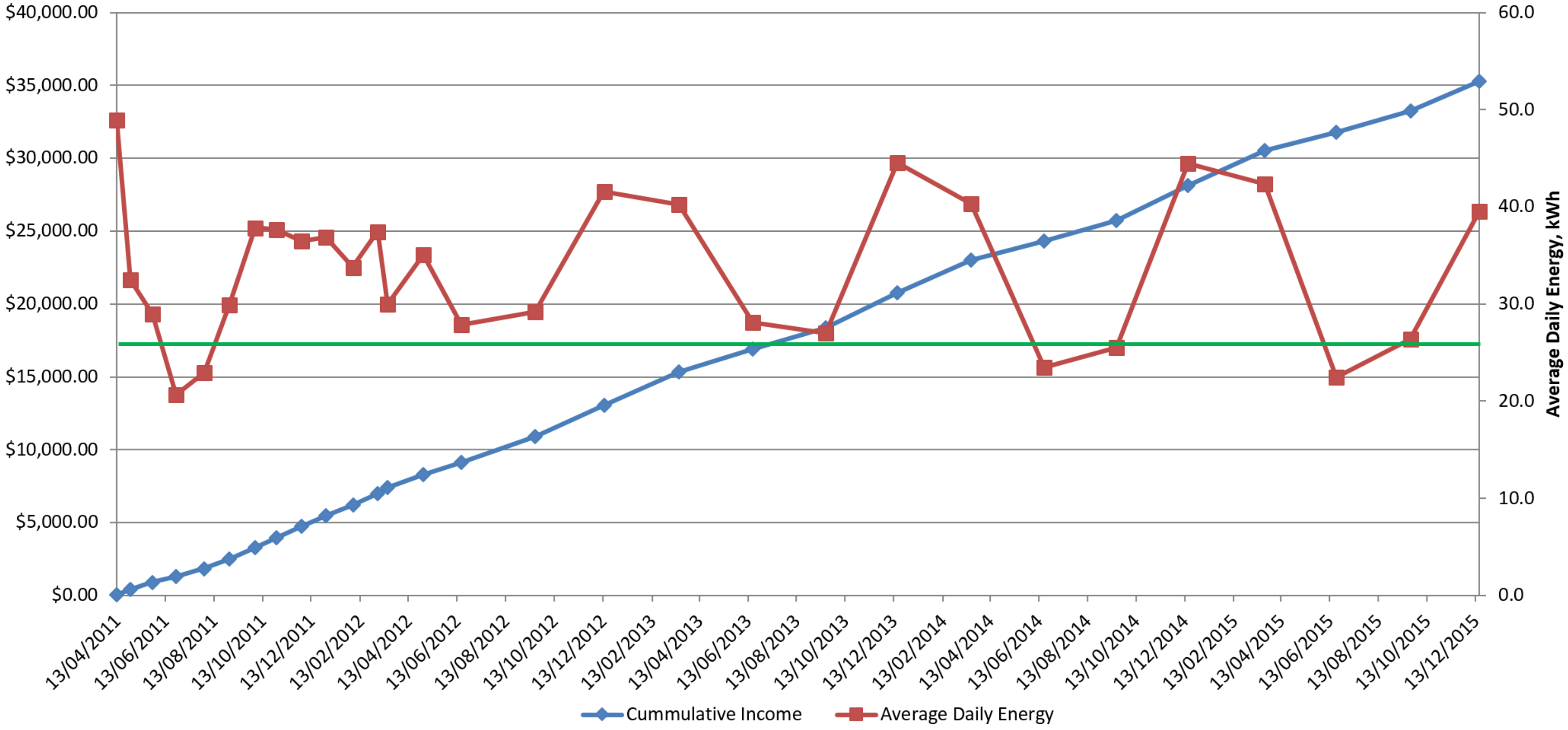

Figure 5: Plot of the historic average daily energy generation of the 10kW solar PV array on the clients' property.